THE CHANGING HYDROLOGY OF THE BARMAH-MILLEWA FORESTS AND ITS EFFECTS ON VEGETATION

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The Barmah-Millway forests are the largest continuous forests of river red gum (*Eucalyptus camaldulensis* Dehnh) in the Murray-Darling Basin. This paper provides an account of work defining the hydrology of these forests. River regulation has changed the forests watering regime and this has and will continue to impact on the vegetation alliances. Change is particularly noticeable in the invasion of the natural "moira grass plains" by river red gum. Unseasonal summer flooding allows germinants to survive the fierce summer droughts, and reduced spring flooding means they are more likely to survive inundation. Grazing also reduces competition from grass. Advances have been made in recent years in viewing and managing both the NSW and Victorian sides as a "whole", in applying hydrologic and hydraulic techniques to practical flooding situations, in obtaining for the forest a "water allocation", and in using remote sensing technology to quantify levels of change. The fundamental problem of securing enough water for the forests to survive and be sustained in the long term remains. Changes in such a forest raise many questions about our society's relative valuing of water as a commodity compared with sustaining the natural ecology of the area.

Key words: Red gum, hydrology, forest, River Murray

THIS PAPER is an account of the hydrology of the Barmah-Millewa forest and the impact that recent changes in this hydrology have on the forest. These changes are associated with changes in the flow of the River Murray due to regulation and the demand for water and tourism services. Fundamental to such an examination is some qualification of the word "forest" – although river red gum (*Eucalyptus camaldulensis* Dehnh.) is the dominant plant (in terms of biomass at least), the area is a mosaic of wetlands, grasslands, and forest. Thus considerations of the impact of change on the forest will include many non-forest areas. Associated with changes in the forest are changes in the limnology of the waterways ramifying through the forest. These may be substantial and important in themselves and are intimately linked to forest flooding. Fig. 1 is a view of a portion of the forest in flood, whilst Fig. 2 is an aerial oblique illustrating a range of plant associations which accommodate different flooding regimes. Fig. 3 is a vertical aerial photograph showing the onset of a flood; in this the water level has reached the invert of a culvert on a road and the water has passed through the culvert to water a small area of forest on the other side.

In presenting such an overview, we must generalise on many points of detail. Of some relevance is that approximately half the forest is in NSW and half in Victoria. The combination of the two states plus Federal involvement in the River Murray can mean fragmentation of information or difference in the treatment of otherwise similar areas. However, in the past two decades there has been a conscious effort by the various agencies to work together to overcome "boundary issues". Notable examples of these are the agreements to "share" rain-rejection flooding so that no one area receives these constantly and the agreement to have similar "regulator" capacity on either side of the river.

THE BARMAH CHOKE

Fundamental to the question of how the forest deals with such flows is an understanding of the channel capacity. Fig. 4 shows longitudinal profiles of the bed and banks of the river and water levels in the river through the Barmah-Millewa forest. It can be seen that both upstream and downstream of the forest the river channel has substantially higher banks (and thus capacity) than in the middle of the forest. At these cross-sections the channel capacity substantially reduces to around 10,000 ML day^{-1}. If flow exceeds this then water passes over the banks

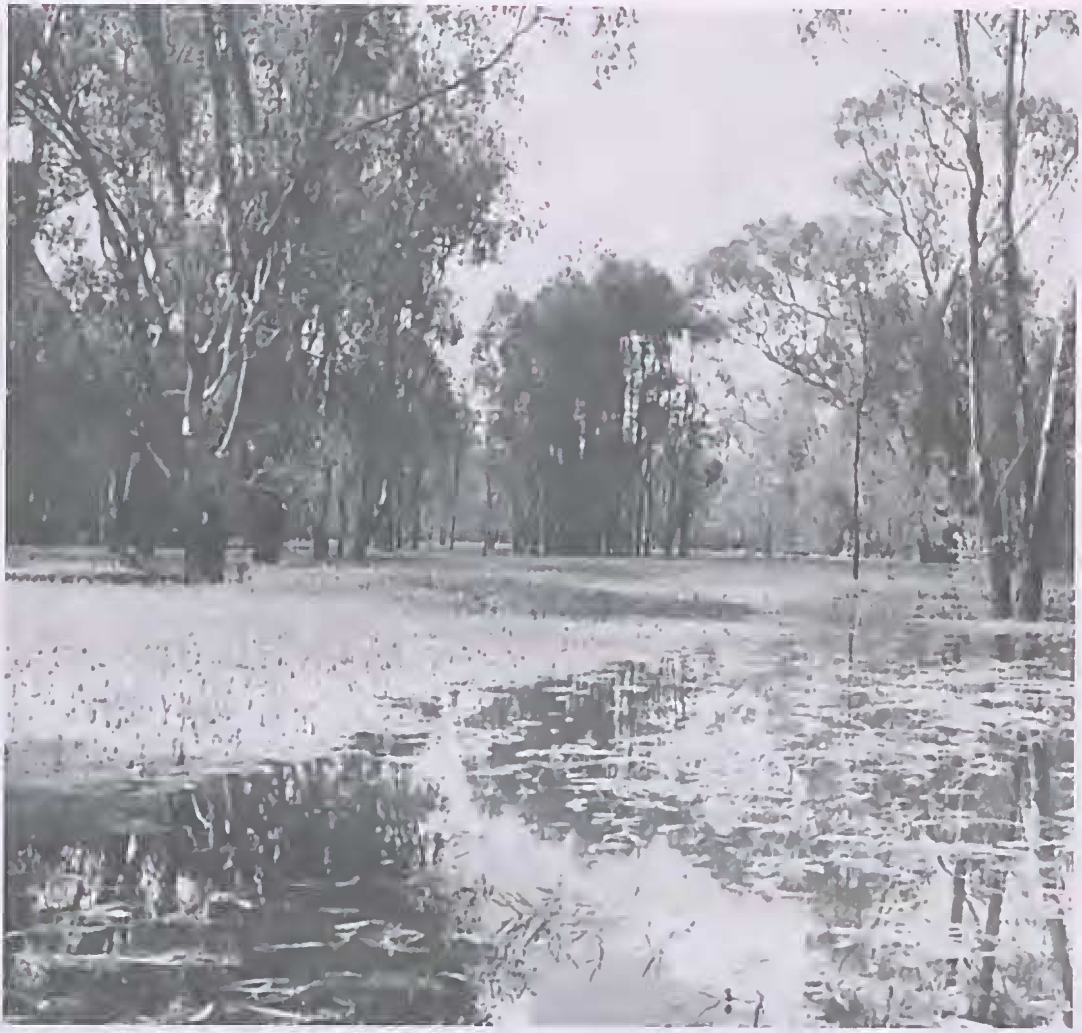

Fig. 1. View of the Barmah Forest in flood.

of the river into the forest. Some of this ultimately returns to the river but most is "lost" to the river by infiltration into the soil or by being trapped in detention storage within the forest. This is a gain to the forest but a loss to the economic water users. The narrow channel – referred to as "the Narrows" or "the Barmah Choke" – is the narrowest section downstream from Lake Hume and limits the irrigation flows passing the forest to around 12,000 ML per day (there is also a limited ability to bypass the Choke by using major irrigation canals). Since most water is stored upstream of the forest, the presence of this section of river is a major constraint on river management.

Over the years the conveyance capacity through the Narrows has been increased, at some detriment to the natural system. Thus removal of obstacles has given a smoother, higher velocity and less turbulent flow, but this has also diminished aquatic habitat. The natural levees have been built up to provide increased depth of flow in the channel. "Effluent streams" have either been blocked off or given regulators (water gates) so that flow is kept in the channels. This, in turn, diminishes the inflow into the forest, thereby depriving the natural ecosystem of "natural" inflows. In all of these, from the forester's point of view, there is a sense of compromise – more water for downstream users at the expense of in-

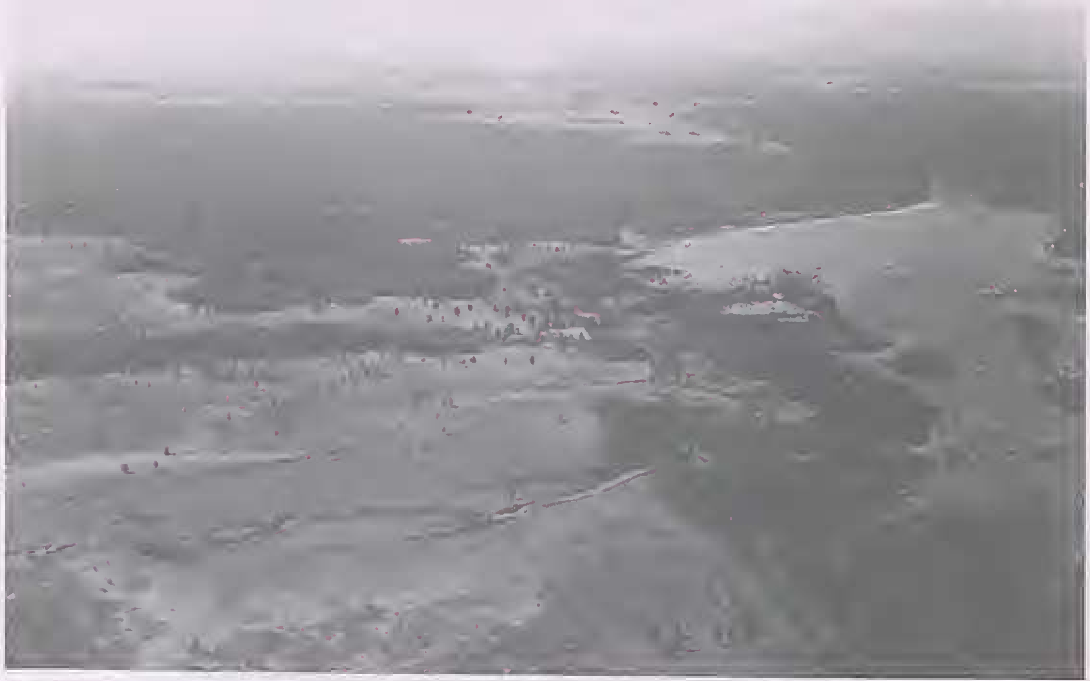

Fig. 2. Aerial oblique of the forest showing the higher flood frequency reed beds and grass plains passing into the lower flood frequency forest areas.

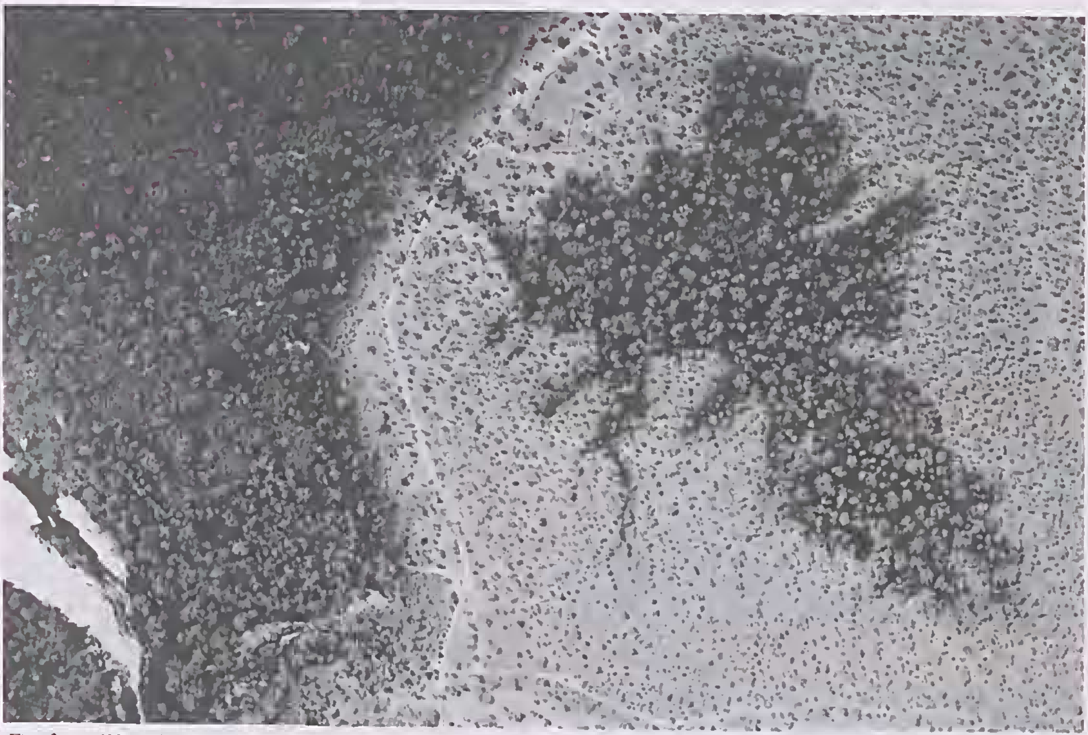

Fig. 3. Water levels have become high enough for water to pass through a culvert invert and wet a portion of forest on the other side of the forest road.

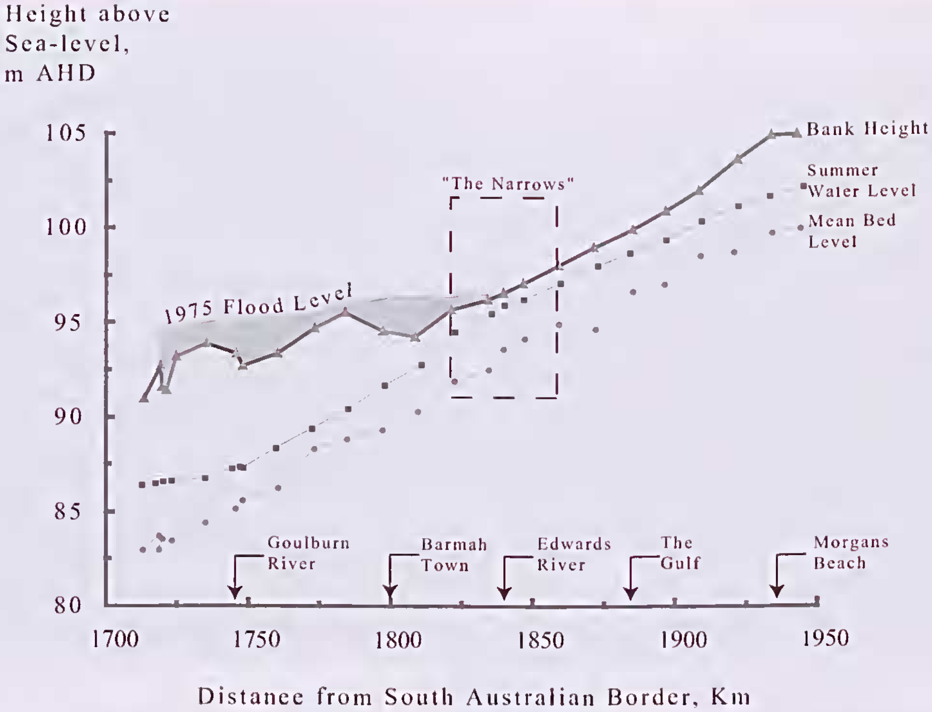

Fig. 4. Longitudinal profile of the banks, bed, and water level in summer and in a flood along the River Murray. The 1975 flood level reflects strong flooding from the Goulburn River (redrawn from Bren 1991).

stream and forest natural values and distortion of the natural hydrologic cycle of the forest.

The need to maximise the flow capacity of the river channel to accommodate downstream flows was appreciated very soon after construction of Lake Hume in the mid 1930's. This led to construction of levee banks and exclusion banks to stop water leaving the river and passing into the forest. The restriction in the number of inlets passing water into the forest was a major change for many areas. It is thought that this change was particularly marked in the Millewa (NSW) side of the forest because of the prevalence of blockage of major inlets and inadequate regulator capacity. To date these impacts have not been quantified, but there has been some increase in diversion capacity into this portion of the forest in the last few decades.

THE ROLE OF FLOODING IN THE FOREST ECOLOGY

The most casual observation of the forest at the time of flooding shows the role of flooding in sustaining life. Before a flood the forest is a quiet place. If it has recently been dry the red gum crowns are sparse, the understorey vegetation is often dry with a greenish-yellow tinge, and there is little evidence of fauna. Once water arrives the forest "comes alive" – the trees develop a heavy, dark-green foliage, birds arrive from other locations, the water proliferates with swimming creatures, and a whole new ecology of plants germinate from within the seed store in the soil. Most observers are struck by the beauty and vitality of the scene. After flood recession, there is a massive shedding of leaf matter, many areas dry out, and the forest returns to a dryland condition. In some cases a fast recession leads to large populations of fish – usually European carp –being trapped in ever-diminishing pools until ultimately anoxia or feral animals finish them off.

The role of flooding in the forest can be quickly, if qualitatively, grasped by comparing the biomass of red gum forests with forests in the same area but which do not flood or receive groundwater from the River Murray. In general the latter have a low biomass, and are composed of drought-tolerant plants able to sustain themselves with an annual rainfall of

400 mm and tolerate substantial summer drought. In contrast, most areas of the Barmah-Millewa red gum forest have a woody vegetation density akin to that of forests of over 1000 mm annual rainfall. The difference is due to the contribution of water and nutrients to the forest as a result of flooding. The floods also reconnect otherwise disconnected waterways and cut-off meanders to the River Murray, allowing an interflow of biota (Young 2001).

The work of Dexter (1970 and 1978) was seminal in defining the relationship between the life cycle of river red gums and flooding. This showed that:

- The trees shed seed at the usual time of flooding. This seed would become engorged and germinated on flood recession. The result of this is long "shore-line" waves of regeneration.
- For seeds shed on bare ground, there was a very heavy loss of seed due to ants and other insects.
- Germinants faced many hazards. The major initial hazard was death from summer drought unless the flooding was unusually late or the summer unusually benign. Unless survivors were tall enough to have leaves out of the water at the time of the next flood they would not survive the inundation. Competition between trees and grasses and exacerbation of frost death of trees in areas of grass were also major hazards.
- If they did survive the summer drought and the next flood, the red gum would have a tendency to grow in very thick clumps as an even-aged forest. For commercial forestry based on timber production, thinning of such clumps was an attractive option.

The forest area has many distinctive characteristics, but amongst the more unusual is the nature of the soil. This can be inadequately described as a deep clay of lacustrine origin, and is probably 30 m or more in depth. Groundwater drilling suggests that at depths of 10 m or more there are usually interleaved sand and clay lenses (eg Bren 1989). The soil does not fit well into usual soil classifications. Of particular importance is its swelling characteristics (Fig. 5). Gerald Auberton (University of Southern Illinois, personal communication) led a program of investigation into the characteristics and showed that it could swell by 5% or more. Massive compaction was unable to achieve a bulk-density of more than about 1.4. However by drying the soil the bulk density could be raised to 1.9 as the capillary forces pulled the soil together. The cracking of the soil is the only "structure." If the soil is cracked at the time of flooding then water will infiltrate deeply into it. If, however, it is swollen as a result of rainfall then there is virtually no penetration. Neutron probe work (Bren 1989) showed that under such a circumstance the soil will dry out because of transpiration by the trees even though there may be 0.5 m or more depth of water sitting on the forest floor.

To the early foresters, the annual flooding of the Barmah-Millewa forest was a marvel akin to that of the flooding of the Nile (Fahey 1988). The advent of river regulation associated with the Hume Dam brought considerable unease concerning changes to the hydro-ecology of these forests. Thus, for instance, in 1932 forester Seaton warned that flooding "would be limited in both height and duration, and surmised that this would affect the vitality of the forest (Fahey 1988). In particular the River Murray Commission quickly realised the problems of passing water through the Barmah-Millewa Choke and raised the natural levees along the river to stop water passing into the forest. This closed off many inlets into the forest, thereby altering the hydrology of the area markedly. Dexter, Rose, and Davies (1986) were the first to quantify the changes in terms of red gum growth, using the criterion of flows in excess of 28,500 ML day^{-1} (averaged over a month) to show that the flood-

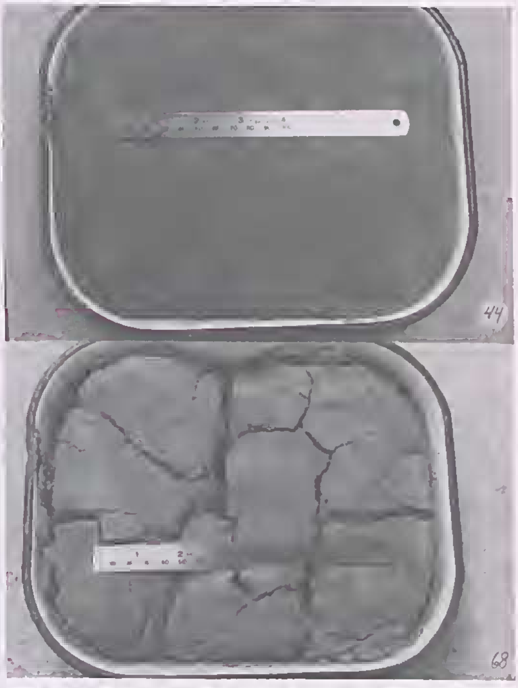

Fig. 5. Barmah soil wetted (top) and allowed to dry (bottom). The cracking nature is evident.

ing depth and duration had been diminished. More recent work has concentrated on the impact of flooding on the forest biota, and has shown that the changes of flooding impact on this biota in many ways.

FLOW CHANGES IN THE RIVER MURRAY

The forest sits more or less in the economic centre of the River Murray system. To the east are the headwater rivers running down from the Australian Alps. These contain the large storages of Lakes Hume and Dartmouth and a myriad of smaller storages associated with irrigation and hydroelectric generation. To the west lie major tourism centres, major irrigation areas, and water users such as Adelaide. The River Murray waters sustain life, commerce, and industry in these areas, and the waters are particularly important in summer. The first effective regulation to meet these needs came with the completion of the Hume Reservoir around 1934. Fig. 6, derived from Bren et al. (1987a) shows measured daily flows (averaged over the period) in the River Murray at Tocumwal for two periods – pre Lake Hume (1910-20, which we will consider "natural") and post Lake Hume (1980-84, which we will consider typical of post-Hume flows). Of particular importance:

- In the "natural case" the river flows would become very low in late-summer and autumn. It would be very unusual to have flows passing into the forest in this period.
- In the post-Hume case (continuing to the present) the river flows are sustained quite close to the 10,000 ML day^{-1} limit imposed by The Narrows for the November to March period.
- Commonly post-Hume summer flows exceed the limit of 12,000 ML day^{-1} (10,000 ML day^{-1} channel capacity and 2,000 ML day^{-1} bypass capacity). Sometimes this is because of heavy rains. More usually, it is because river diverters between Lake Hume and the forest do not choose to take allocated water and there is inadequate storage space in Lake Mulwala to store the additional water. These flows are referred to as "rainfall rejections". Typically these flows spill into low-lying parts of the forest. Soon after regulation many of the forested wetlands are thought to

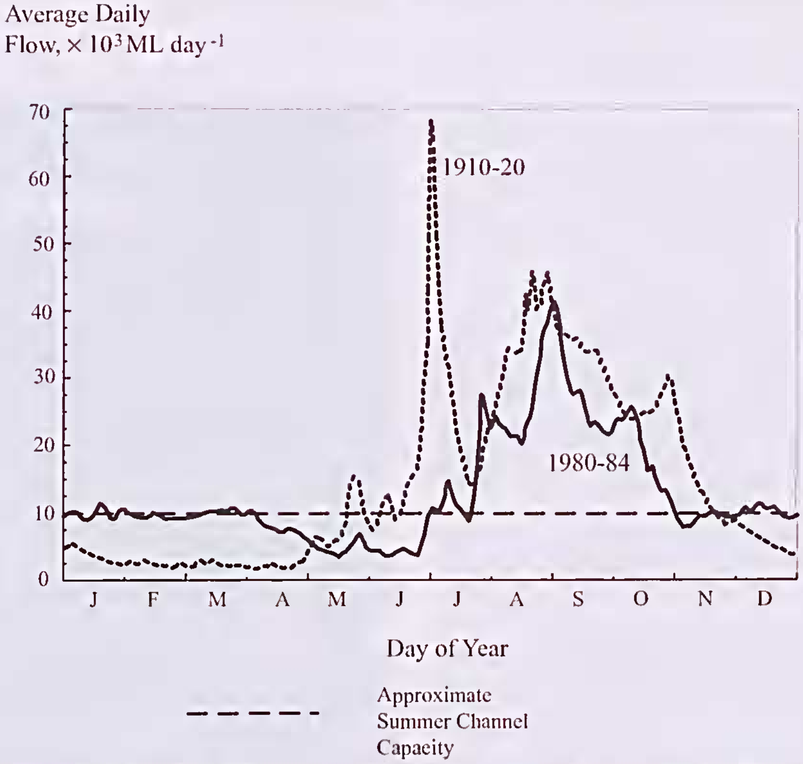

Fig. 6. Average daily flow in the River Murray at Tocumwal for a pre-Lake Hume period (1910-1920) and a post-Lake Hume period (1980-84). The capacity of the "Narrows" (10,000 ML day^{-1}) is also shown (redrawn from Bren et al. 1987a).

have changed their nature from intermittent to permanent wetlands, and this led to death of red gum trees in these areas.

- In late-winter and early spring the flows pass over the banks or through "regulators" (water-gates) into the forest. Historically the flows have exceeded the regulation capacity of the River Murray and essentially the system reverts to being "natural". However in recent years diminished flows associated with drought have reduced such inflows.

Thus the essential pattern of flow change forced on the forest is the introduction of summer flooding, albeit with small volumes of water, and the reduction in winter-spring flooding. Although there have been some variations of this in recent years associated with environmental flows, the fundamental pattern of regulation-induced changes remains. A consequence has been that wetlands and lagoons directly connected to the river may not have a "drying out" period, thereby changing their ecology – some remediation for this will be discussed below. There are also associated changes with water quality because of the storage involved. The flooding can be viewed as having a "managed component" associated with opening of regulators to allow water to pass in to the forest and a natural component reflecting that ultimately control of the water is lost as the flows increase and the waters overtop the river banks.

Bren et al. (1987a & b) correlated river flows in the River Murray with the extent of flooding in the forest using a sequence of annual flooding maps of the Barmah Forest. The best predictor of flooding was found to be the peak annual flow at Tocumwal, with the relation derived being:

$$P_{\%} = -435.40 + 47.60 \ln(Q_p) \quad Q_p < 68{,}500 \text{ ML day}^{-1}$$
$$P_{\%} = 93.5 \quad Q_p > 68{,}500 \text{ ML day}^{-1}$$

where $P_{\%}$ is the percentage of the forest inundated and Q_p (ML day^{-1}) is the maximum daily flow at Tocumwal during the period of inundation. Fig. 7 shows this relation and the points used in its derivation. This relation was then used to provide estimates of the monthly flooding and to reconstruct flooding patterns across the forest. Fig. 8 shows estimated averages of the distribution of flooding in the Barmah Forest for each month pre-Hume and post-Hume Reservoir. The results suggest that:

1: Summer flooding is quite common post-Hume, reflecting the passage of regulated flows and "rainfall rejections".

2: Post-Hume, the average flood is substantially diminished in winter-spring, and the variability of flooding is increased. For instance, in the pre-Hume September, it was almost certain that most of the forest would be flooded. In the post-Hume period to the present it is likely that there will

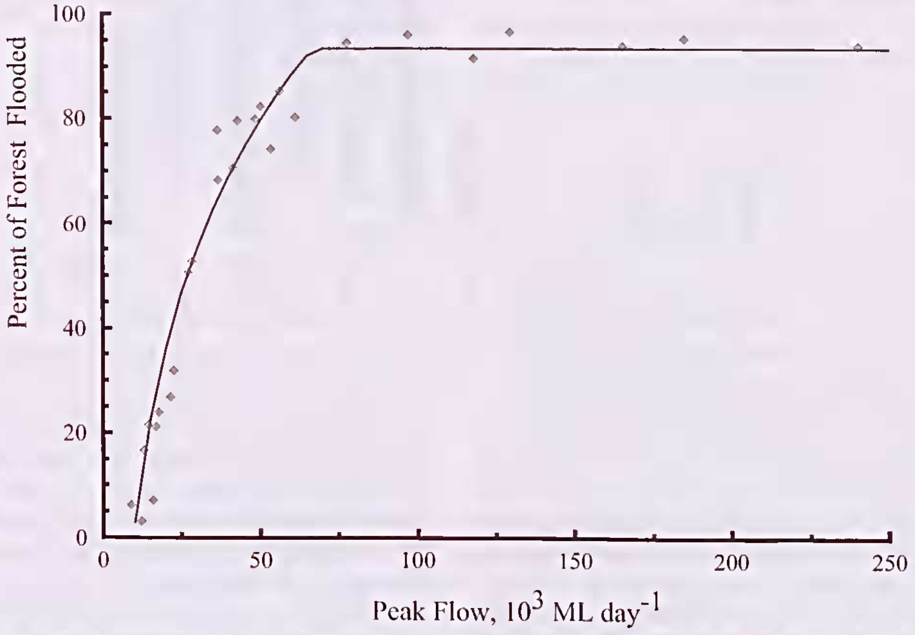

Fig. 7. Relation between peak flow in the River Murray and percentage of the forest flooded (redrawn from Bren et al. 1987a).

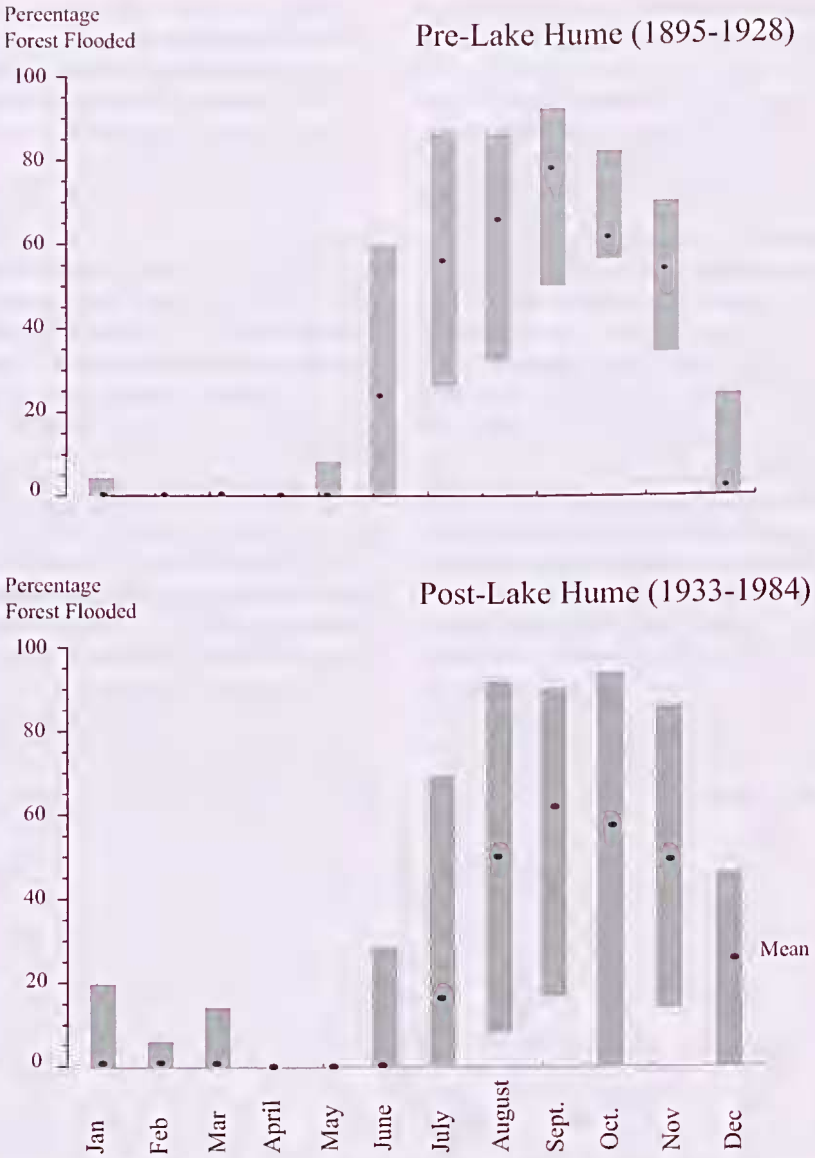

Fig. 8. Monthly distribution of the mean, 25%, and 75% percentiles of forest flooding for the pre-Lake Hume and post-Lake Hume periods (redrawn from Bren et al. 1987a).

be substantial flooding in the winter-spring months, but this is less certain.

More recent work has had two threads. The first of these is the development of modelling by the Murray-Darling Basin Commission (eg Anonymous 1997). This allows good estimates of what the flow in the River Murray at key points would have been with and without river regulation. This has allowed quantification of much flow change and assessment of effects and evaluations of alternative flow management strategies for water passing the forest. The second thread has been the recent application of LIDAR technologies to allow forest floor mapping. LIDAR involves an aircraft-mounted active sensor and can give accurate spatial measurements of the height of the forest floor above a datum. This, in turn, can be used in large-scale hydraulic models to go from river flow estimates to estimates of what happens at a particular site (eg Maunsell Australia Pty Ltd 2003). Although both developments offer much potential for the future, the sheer work load in applying either of these to such a large forest must not be under-estimated. The level of computational expertise and the "in-house" nature of such technologies also means that the work and results tends to be the "property" of the agency that undertakes works, and so can not be independently assessed or challenged.

IMPACTS OF HYDROLOGIC CHANGE ON THE VEGETATION

To a first approximation at least, the vegetation can be viewed as the passive receiver of water. By a process of natural selection, the vegetation that results reflects the availability, depth, and duration of flooding. Table 1 below gives an ordering of some major vegetation associations that are found in the Barmah-Millewa forest. The classification follows the ordering of Chesterfield (1986) and was derived by Bren and Gibbs (1986). This table is misleading for the more ephemeral vegetation however. Thus reference to "moira grass plains" suggests that moira grass (*Pseudoraphis spinescens* Vickery) is a "dominant" and "permanent" feature of these areas. In fact work by Keith Ward (Personal Communication) and others has shown that it is anything but this – the moira grass comes and goes in a sequence of vegetative growth. Thus after a long, wet period the sites may be dominated by water milfoil (*Myriophyllum spp.)*, which as it dries may pass into moira grass, which as this dries may be replaced by other grasses, and so on. Nor is there particular evidence of "cycling" of species; species certainly come and go but not necessarily in a regular procession. A more recent and excellent account of the water regime of wetland plants found in this area is given by Roberts and Marston (2000).

For much of the "forest" the most visible plant is river red gum. For humans at least this gives the forest its characteristic look and feel – an open forest, with large, old trees intermixed with slim, clean regrowth and grass underneath. Almost uniquely for Australian forests there are no other woody species growing in many areas; this in turn makes the forest very open. It has been well-established (eg. Dexter 1978) that the vigour and growth of the red gum reflects flooding – in general, the more flooding the more vigorously the trees will grow. However the trees are able to withstand long periods of drought and are not particularly sensitive indicators of hydrologic change (although the vigour, colour, and density of the crown may reflect the state of moisture stress). In contrast, the understorey will also reflect the flooding history and, for much of the forest, hydrologic changes equate to changes in the understorey. Thus a moira grass understorey may be replaced by warrego summer grass, which in turn may be displaced by bare ground...etc. In some cases the flooding frequency has dropped enough to allow invasion by weed species. However these changes are also masked by the dynamics of the vegetation. Thus good rains will induce a flush of grasses, reflecting a seedbank of vegetation. Hence valid observations need a good, long-term base to be used for inference.

We can, however, find more permanent indications of change in areas at the margins of red gums' existence. These are usually the very driest and the very wettest areas. In the driest areas red gum is replaced by various box species. The change is slow in human terms; even stressed mature red gums live for a long period by human standards. Further, most of the driest areas have already been removed for farming settlement so there is little evidence of this change. At the wetter end of the spectrum however things are a little clearer. Two particular effects can be noticed in an intricate and intermingled pattern – firstly red gum can be flooded out to the point of death, and secondly red gum can be favoured to invade areas of what were hitherto natural grasslands.

The first effect – death by excessive inundation – was noticed relatively soon after the introduction of river regulation around 1936. High river flows and rainfall rejection flows caused almost permanent flooding of the lowest areas adjacent to the river (eg. St Helena Swamp in NSW). The trees ultimately appear to develop tyloses (blockages in the wood vessels), fungi invades the wood, and the trees die (ironically of drought stress because of loss of water-conducting tissue).

The second flood-related change affects one of the (arguably) prettier ecosystems – the "Moira Grass Plains". Fig. 9 gives a view across such a plain. Fig. 10 shows the same area of "Moira Grass Plains" in 1947 and 1984. The 1947 photograph shows the process of digitate delta formation on these plains associated with sediment deposition. The second photograph shows "invasions" of the plains by regrowth red gum. Bren (1992) examined this process and found that the plains are a diminishing ecosystem, and this process has not reversed in the years since then. Although it is hard to be certain of "cause and effect" the factors could be viewed as:

1: Grazing has diminished the density of the grass on the plains. In natural situations Moira grass is a fierce competitor for moisture and young red gum seedlings can usually not survive the competition. Thus diminishment of the density reduces this factor.

2: Summer flooding has assisted the young trees to survive through the heat of summer. Dexter (1978) showed clearly how difficult this is for young trees in an entirely natural environment, and

3: The reduced winter-spring flooding has again allowed young trees to survive in what once were high flood frequency sites. Again the work of Dexter (1978) showed the difficulty for trees in surviving complete inundation. Reduced flood depth and duration has made it possible.

In terms of probability of survival of an individual seedling, the change is small, but because of the vast amount of seeds shed, the impact is substantial. The net result is that much of this interesting ecosystem is being extinguished by invading red gums. The predictions of Bren (1992) were that by 2056 the ecosystem would have effectively ceased to exist, and that seems to be coming true. Thus the large areas of grass plain are being replaced by a more intimate ecosystem of plains and trees. This has caused concern and a number of schemes have been considered to reverse this. In particular a trial was made of fuel-reduction burning in 2000 ("Project Firestick") to see whether this would kill seedlings (Bren and Acenolaza 2003, unpublished report). Two difficulties in this strategy stood out. The first was of having enough fine fuel-load in the grazed grass plains to sustain an adequate fire intensity for fuel-reduction burning. The second was of finding a "window" in which to burn between the cessation of the fire-season and irrigation season and the onset of winter-spring flooding in these areas. In the "Project Firestick" trial, fuel had to be carted to the burning plots to sustain combustion. Unusually high winter flooding following the burning trial killed seedlings on the controls as well as any surviving seedlings on the burnt plots so the results were not conclusive as to whether burning would make a good ecological strategy (assuming it was feasible). Other suggestions include clearing or cutting the regrowth invaders but this hardly seems commensurate with conservation values in a national park.

More recent work has focussed on smaller elements of the vegetation. Particularly seminal in this area is the work of Robertson et al. (1999) looking at the transformation of organic carbon in Australian flood plain rivers and using the Barmah Forest to investigate and follow such changes. This work fo-

Flood Frequency Class	Vegetation Alliance	Approximate Flooding Frequency, n in 22 years	% of Area
Very high	Giant rush	16-19	1.8
High	Moira grass Red gum and moira grass Red gum regeneration on plains	15-18	23.4
Moderate	Red gum in conjunction with sedge, warrego grass, wallaby grass, and swamp wallaby grass in various combination.	12-16	57.7
Low	Red gum & introductions Red gum, wallaby grass and spike rush Yellow box and black box woodlands	6-10	17.1

Giant rush (*Juncus ingens* N.A. Wakefield), Moira grass (*Pseudoraphis spinescens* (R.Br.) J.W. Vickery, sedge (*Carex tereticaulis* F. Muell), Warrego summer grass (*Paspalidium jubiflorum* (Trin) D.K. Hughes), wallaby grass (*Danthonia racemosa* R.Br.), swamp wallaby grass (*Amphibromus neesii* Steud), spike rush (*Eleocharis acuta* R.Br), yellow box (*Eucalyptus melliodora* A. Cunn. Ex Schauer), black box (*Eucalyptus largiflorens* F. Muell.)

Table 1. Vegetation associations delineated by Chesterfield (1986) grouped by their characteristic flood frequencies. A fuller enumeration of the alliances is given in Bren & Gibbs (1986).

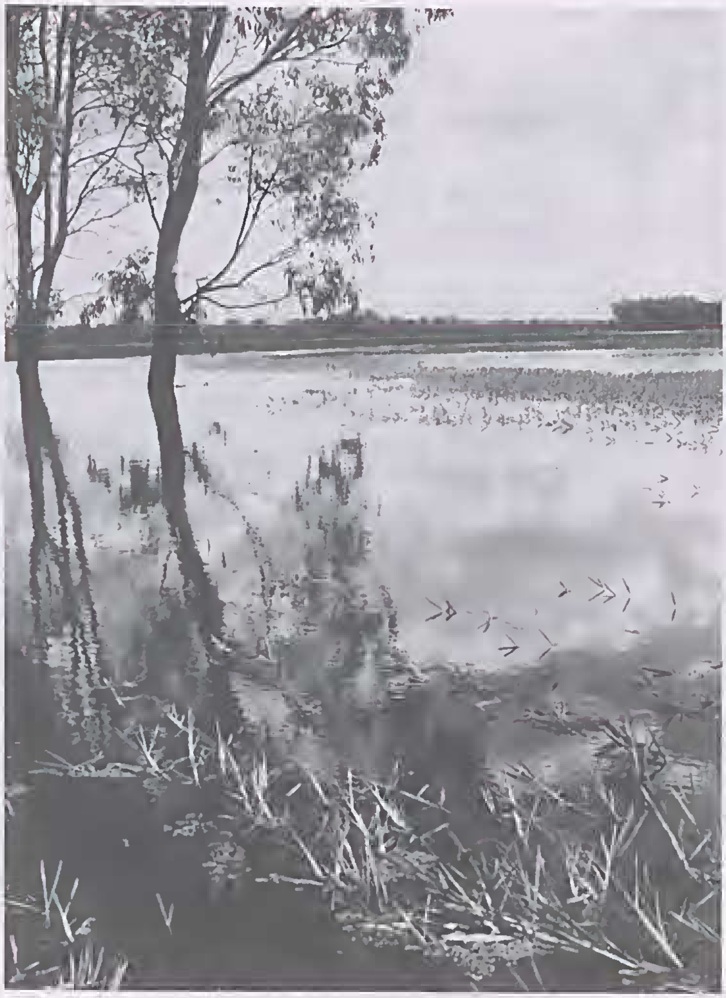

Fig. 9. View across a moira grass plain at the time of flooding.

cuses on the role of natural flood regimes in stimulating bacterial growth associated with decomposition. Indicators used are biofilms – thin layers of microbial matter forming on woody debris and the forest floor as a result of inundation. These provide "feeding matter" for a diversity of life forms found on the forest floor. The direction of this work also indicates an enhanced and increasing interest in non-commercial biota in the forest.

HYDROLOGIC CHANGE INDUCED WITHIN THE FOREST

Clearly the hydrology of the forest can be viewed, to a first approximation, as a "forced function" of the River Murray flows. However there are various factors internal to the forest that can also change the hydrology of the forest and these can be quantified to some extent.

First of these is the hydraulic properties of the network of channels carrying water from the River and through the forest at times of moderate floods. These waterways probably also transmit most of the water at higher flows but can not be distinguished easily since the water surface becomes a large sheet. Sediment deposition and scouring would influence their conveyancing ability, but a major determinant must be the flow of large, woody debris into these. This would provide hydraulic roughness and greatly retard the ability of the channels to transmit water into the forest or convey water out of the forest. Related to

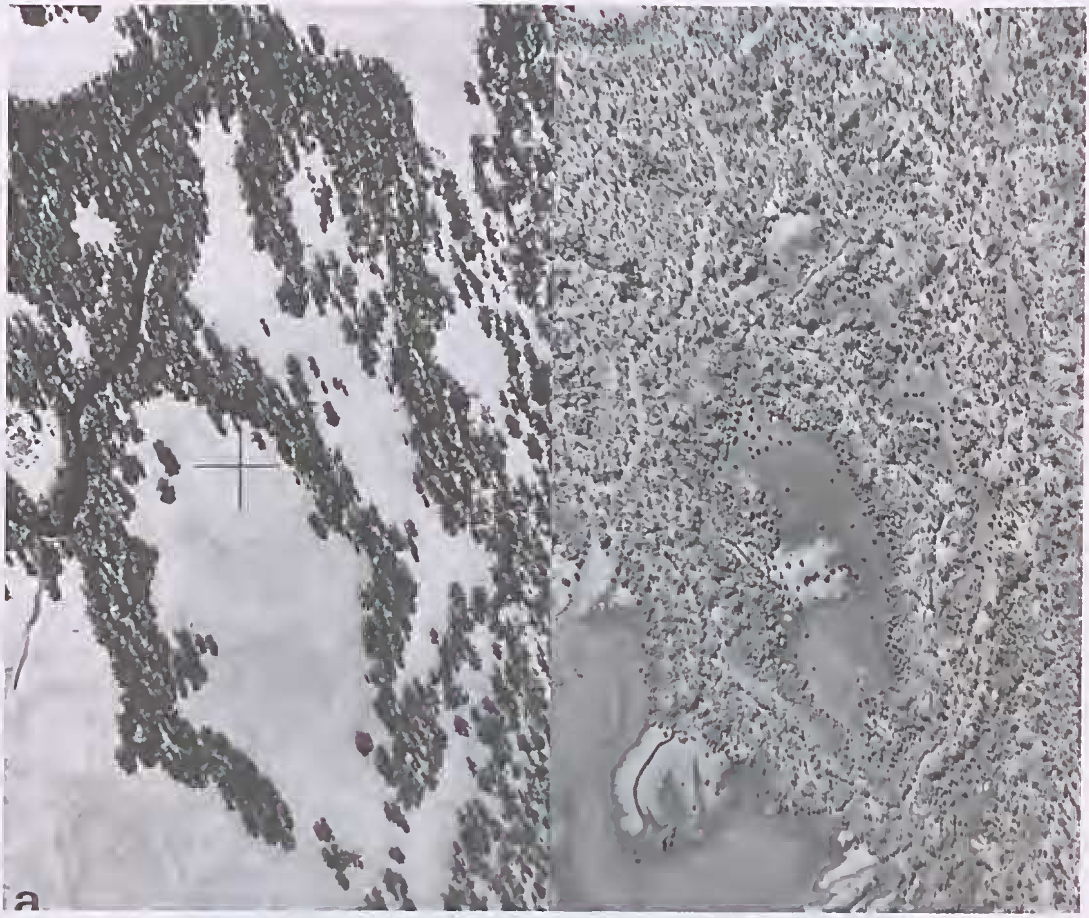

Fig. 10. Comparison of the forest-grass edge of an area of moira-grass plain in 1947 and 1984. The invasion of red gum can be clearly seen. Photographs courtesy of the then Department of Property and Services of the Victorian Government.

this is the question of whether water passing into a forked junction favours one branch or the other. The hydraulics of behaviour at forks in channels is not well-explored and appears to depend on a delicate interplay of factors, but is particularly influenced by small changes in water turbulence (although the phenomenon is hardly explored in hydraulic literature). Thus you could view this channel network as being a chaotic system in which, irrespective of how similar the human inputs might be, the behaviour (in the sense of where the flow ends up) would differ over time because of the additions and removals of large organic debris. One can certainly show that the upstream turbulence (which is a function of the woody debris) will play a major role here.

Second is the question of hydraulic resistance of the forest to flow. A personal opinion is that the forest is much more freely draining than it used to be, reflecting that the lower flood frequencies have reduced the area of reeds and rushes along the waterways. Thus water can leave the forest and return to the river more easily than it once would have. Again the flow of large woody debris into channels and on the forest floor would pay a large role here. One can also define many other factors such as whether the soils are cracked or closed at the time of flooding, regrowth versus old growth, and vigour of grass swards that may influence this, but more research needs to be done.

Third is the case of making inadvertent change to the channel network of the forest. Fig. 3 illustrates that the level of a culvert invert can have a big influence on whether a portion of a forest receives flooding. Throughout European occupation of the forest, people have been digging channels here and blocking channels there to facilitate some shortterm goal. Thus timber-harvesters would often block waterways to extend their logging season, hunters would block drainage from a pond to facilitate bird-breeding, and settlers would block waterways to stop flooding of their land. These blocks would usually not be removed. In most cases the subsequent floods would rearrange things, but in some cases there is known to have been a definite influence. This could be viewed as a chaotic pattern of modification which can certainly modify the environment of some areas.

ENVIRONMENTAL FLOWS AND REGULATED WATERINGS

There have been three approaches to overcoming the issues associated with River Murray changes. The first is the use of small earthen walls ("low banks") to contain and channel flow. The second is "managed floods" using an environmental flow supplement. The third is to "dry out" wetlands to attempt to reproduce the natural intermittency of flooding. Each of these is incorporated to some extent in the Barmah-Millewa Forum (2003) annual plan.

Low Bank Works

In the natural situation water flowing into the forest would either infiltrate or flow away. A low bank is a small earthen wall strategically placed so that added water will remain in place and infiltrate or give the plants time to absorb it. These have been used with moderate degree of success. Typically the "watering" is done in summer and autumn when the areas are accessible. Water is added, preferably by using the hydraulic head of the water to allow it to flow in. The water remains ponded until the watering is judged as sufficient, at which point it is drained off using a water-gate. The technique does require extensive but low-level earthworks including maintenance of channels and construction of earthen walls at a uniform, appropriate height. For optimum use there is a need for excellent record keeping and for skilled staff members to manage the watering. Although effective in stimulating tree growth, the method is quite expensive and requires a considerable labour input (Maunsell Pty Ltd 1992). Perhaps a major drawback of the technique is that it caters for the red gum trees but does not have the same beneficial impacts on the understorey. Construction of the earthen structures can be a source of disturbance.

Managed Floods

The Murray-Darling Basin Commission has allocated (potentially) an environmental flow of 100 GL year^{-1} (measured passing through Tocumwal). The use of this water is governed, however, by complex rules as to when it can be released and the rate of transmission downstream to avoid flooding of farmland and erosion of river banks. This water, when added to existing flow, would raise the head of river water, allowing it to pass into the forest and "water" areas that would otherwise not be watered under the current flood regimes. Major releases were made in 1998 and 2000. In the latter case there had been an intense but short-lived flood from the Ovens River. The purpose of this "top-up" release was to slow down the recession in the forest and to push water further into the forest than it would have otherwise gone. The combination of natural flooding and the environmental release resulted in 91% of the Millewa Forest and 85% of the Barmah Forest receiving an inundation. There was also a successful breeding of colonial water birds in 2000/2001 (Barmah-Millewa Forum 2001).

Managed floods have a role in reducing the impact of river regulation, but at best they are hedged in by many compromises to do with limiting flooding of non-forest areas, availability of water, "prioritising areas", and the difficulty of creating a high-enough flow to push water to more remote parts of the forest. The subject requires a considerable amount more work.

Managed Drying Out of Wetlands

The higher summer and autumn water levels have led to high water levels in directly-connected lagoons such as the Moira Lakes. The result has been that the deeper, permanent water has led to the elimination of intermittent wetland species. The water has become too deep for many water birds to use effectively. Leslie (1995) showed the historic biodiversity productivity of these lakes prior to river regulation. The loss of this productivity associated with river regulation must be viewed as a major environmental change. A major project on the northern Moira Lake has been to restore a "drying out" phase by building water exclusion structures along the inlet channels. This has led to significant vegetation changes, although the full significance has yet to be assessed. Although such drying out may be viewed as a "move towards returning to a natural flooding regime" there are many difficulties in implementation including cost of construction and operation, loss of irrigation water storage, resistance by people who had become accustomed to the permanent inundation, and differences in the expected and the observed response of the dried-out wetlands.

Increased Diversion Capacity

In recent years additional regulators have been built to allow water freer entry into the forest; in particular the "Mary Ada" regulator allows about the same entry capacity into New South Wales as the "Gulf" regulator allows in Victoria. Experience has also been gained in NSW in husbanding flows to certain areas of the forest using channels, culverts, and water gates so that areas of the forest "get a drink."

Over the last decade there has been a large amount of work on development of forest watering plans (eg. Barmah-Millewa Forest Water Management Plan 1998). Associated with this has been work on distribution of flood waters, studies of specific floods, and examinations of the "environmental water allocation" for the forest. These give a reasonably guaranteed future forest watering regime for at least some of the forest.

DIRECTIONS FOR FUTURE RESEARCH

For the keen researcher there are a number of directions that might be explored:

1: The use of new, laser-measured topographic data in hydraulic models and comparisons with field measured data should yield good insights into how water behaves as it enters and leaves the forest. A major difficulty in this approach has been and will be "verification" of the resulting model.

2: Continuation of measurements of groundwater levels in the forest, and studies of the impact of groundwater pressures on the water economy of both the trees and understorey. Quantification of the role of cracking in the water economy of the forest would add much to our understanding.

3: Long-term observations of vegetation change and relation of these changes to causes.

4: Measurements of the behaviour of water in the forest at various flood levels, including the question of factors influencing the behaviour at water forks, and the hydraulic resistance of forest and associated channels.

5: Simulations of what might be achievable with use of environmental flows; in particular, can these be used to "water" more remote parts of the forest.

6: Elucidation of the paleohydrologic factors that led to the formation of the forest, and the role of past and future climate change in the existence of the forest.

On a more philosophic note, there is the question of what a "natural red-gum" forest is and whether a managed watering regime can "mimic" the natural regime. One could even ask whether this is a desirable goal if a "natural" River Murray is no longer possible. We can not pretend that any of these research topics would be easy to undertake.

THE WAY FORWARD

In general, there is no lack of goodwill towards the forest by other water users. The basic issues associated with long-term environmental changes in the red gum forests relate to the value or necessity of access to water for downstream communities, coupled with major potential changes in the climate. These can be crystallised into a number of points:

1: A desire to overcome the flow restriction posed by the Barmah Choke, so that water can be moved from upstream reservoirs to downstream consumers at a higher rate. At the moment this is effectively a 12,000 ML day^{-1} rate before the forest becomes flooded. Alternatives suggested include increased bypass capacity by channels running around the forest. This in turn would have serious ramifications for the reaches of the river affected.

2: A rainfall pattern which may be exhibiting long-term changes, such that the rainfall regime of the last century is not representative of the regime of the coming centuries.

3: A strong desire for conservation of the forest area and associated ecologies, and to protect them from further ecological change. This is particularly manifesting itself in a move away from management of the forest for wood production in favour of biodiversity management.

4: The realisation that water is a very valuable resource, the development of trading rules for water, and the desires by communities to extract more water from the River Murray to enhance economic growth.

These pose a number of significant issues for the forest and river managers. Most important is the philosophic question of whether a flood regime that mimics a pre-Hume Reservoir flood regime is either achievable or desirable. An alternative would be to allow the forest to reach some sort of "equilibrium" with the evolving river (and associated flood) regime. Related to this is a series of technical questions as to whether such a flood regime is possible on grounds of water availability and the problems of water distribution. It will be interesting to see which way the community moves on such complex and intertwined matters.

CONCLUSIONS

The Barmah-Millewa forest ecology is intimately linked to flooding from the River Murray. This flooding provides much of the water for transpiration by the plant alliances. The flooding, in turn, is linked to the subdued but very real topography of the forest, giving a quite strict zonation of the communities. Because of other community values placed on the flow of the river, this has led to changes in the flooding regime. In particular, small summer floods frequently occur due to the lack of "air-space" in the river and regulating storages. Thus unplanned flows associated with rainfall or irrigation rejections flood the forest. Equally the substantially larger winter-spring flooding has been diminished because of the need to store water for irrigation. The result of this is changes in the ecology, including a diminution of vigour in the lower flood frequency parts of the forest, and a change in understorey species. In some cases red gum has invaded sites that would have once been inaccessible to it because of grass competition. Although the forest is clearly changing as the river changes, there are interesting philosophical questions as to whether management should attempt to conserve the forest in a pre-regulation model, or accept a changing water use and ecology.

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